

# GALILEO PROBE THERMAL CONTROL

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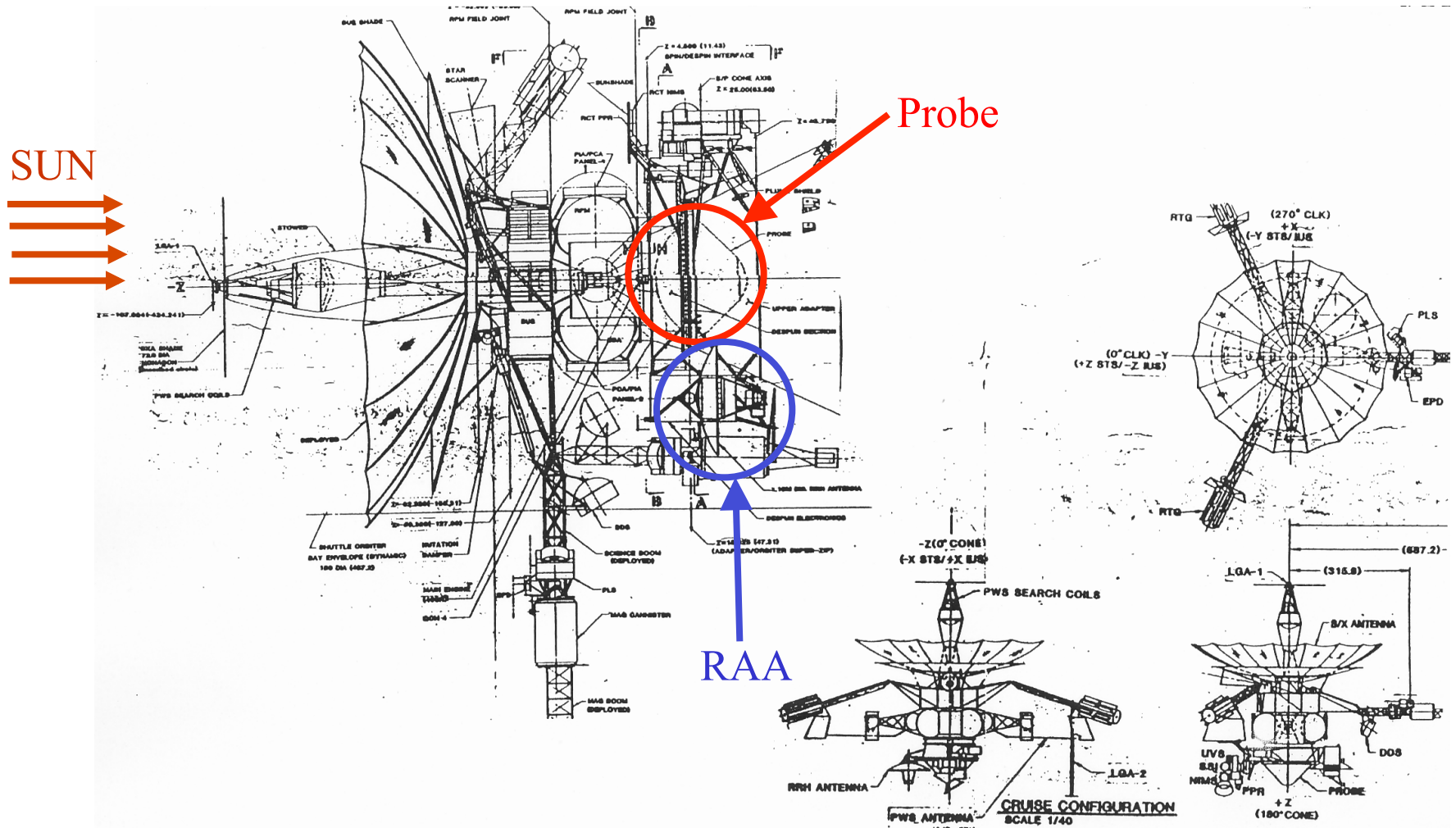
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- **Boeing Satellite Development Center (BSDC) formerly known as Hughes Space & Communications Company provided the Galileo Probe system & Orbiter mounted relay radio hardware (RRH)**
  - Galileo VEEGA (Venus-Earth-Earth Gravitational Assist) mission began 18 October 1989 launched on Space Shuttle Atlantis (STS-34)
    - first in-flight Probe check-out 8 days after launch, all systems nominal
    - second in-flight check-out December 1990, 4 days prior to Earth fly-by
  - Next major event April 1991 when Orbiter High Gain Antenna (HGA) failed to deploy (HGA was not the responsibility of Boeing)
    - maneuvers to thermally cycle the HGA mechanism were conducted from late 1991 through early 1993, used CTE mismatch to free mechanical hang-up
      - BSDC responsibility was to make sure Probe & RRH not damaged by maneuvers
      - resulted in cycling & elevated temperatures of BSDC hardware as compared to initial design for stable cold soak
  - Final Probe check-out March 1995 followed by Probe release July 1995
  - Probe descent & encounter were successfully executed 7 December 1995
    - BSDC support extended through October 1996 due to loss of HGA
      - Low Gain Antenna (LGA) 10,000 times slower data rate than HGA
      - longer playback time, but still 100% successful Probe mission with no HGA

- **Three main phases of Galileo Probe mission**
  - Cruise is time from launch until Probe is released from Orbiter
    - cruise duration was approximately 6 years for Galileo Probe
      - gravitational assist by going around Venus & back around Earth (VEEGA)
      - spacecraft gathered data on Gaspra & Ida asteroids & Shoemaker-Levy 9 comet
    - maneuvers intended for HGA mechanism cycling occurred during Cruise
  - Coast phase includes time from release from the Orbiter until encountering Jovian atmosphere
    - temperatures verified to be within  $\pm 3^{\circ}\text{C}$  of predicts just prior to release
    - Probe timer activated 6 hours prior to entry, almost dead center of window
    - coast duration approximately 150 days, no telemetry during coast
    - data 3 hrs. & 20 min. prior to entry show Probe temperatures  $-3^{\circ}\text{C}$  to  $2^{\circ}\text{C}$ 
      - this is as close as possible to the  $-1^{\circ}\text{C}$  predicted prior to launch
    - no additional thermal discussion of Galileo Probe coast phase, uneventful
  - Descent phase is from the time the Probe entered the Jovian atmosphere until it stopped providing data back to the Orbiter (end of its mission)
    - two notable conditions seen during Descent, one thermally related
    - Probe mission 100% successful with HGA & two minor Descent anomalies
      - shows adequate implementation of redundancy & thermal margin

## •Layout of Probe & RRA on Spacecraft during Cruise



- **RRH hardware: receiver, oscillator (USO), RR Antenna (RRA)**
  - RRH units in well controlled thermal environment within Orbiter
    - receiver & USO standard electronic unit allowable temperature ranges
      - non-operating survival temperature range -20°C to +50°C
      - operating temperature range -10°C to +50°C
    - temperature telemetry within allowable range during all mission phases
      - larger variations than seen on Probe due to changes in Orbiter configuration
      - all temperatures between -2°C to 23°C, spikes up to 37°C when operated
      - RRH unit temperatures during Probe descent 35°C – 37°C
      - did not change at all during 1 hour descent, met stability requirement
    - no issues with RRH units thermal control during any mission phase
  - RRA external to orbiter, facing away from sun so extremely cold
    - samples tested in liquid Helium for exposure to -220°C, well below LN<sub>2</sub>
    - special investigation into solar loading being concentrated onto antenna feed cup during HGA maneuvers, not designed for exposure to sun & cycling
      - photometric mapping allowed ambient P/T verification of focused energy
      - collimated light source & photometer determine if multiple sun loading occurs
      - performed test on old Qualification RRA shipped from JPL to BSDC
    - RR antenna performed as predicted during all mission phases

- **Cruise Probe thermal performance as predicted prior to launch with additional analysis of HGA maneuvers**
  - Goal to maintain Probe temperatures at 0°C & stable
    - optimal storage temperature for Li/SO<sub>2</sub> main Probe batteries
    - safe temperature for “off” electronics units & no thermal cycling
    - Probe thermal control consisted of MLI blankets (>50 layers), low ε gold tape external surface, 36 radioisotope heater units (RHUs)
  - Telemetry showed all temperatures between -3°C & +3°C
    - some telemetry reached -4°C just prior to release
    - well within Probe main battery Acceptance range of -15°C to +20°C
      - other hardware had wider allowable temperature ranges
  - Only exceptions were during HGA maneuvers
    - turn HGA away from sun, resulted in Probe & RRA turning into sun
      - attempt to free mechanism by cooling it, resulted in Probe & RRA warming
    - approval from battery experts as well as extensive review of other hardware designs to go to 40°C for 13 planned HGA excursions
    - two flight rules limiting maneuver angles & distance from sun implemented as result of HGA maneuver thermal study
      1. any maneuver over 165° limited to outside 1.45 Au, Probe/Orbiter Separation device ≤ 71°C
      2. any maneuver over 90° limited to outside 1.30 Au, RRA dipole ≤ 100°C
    - only 7 excursions actually executed, telemetry showed 33°C reached within Probe
    - did not free stuck HGA, also did not harm Probe/RRH hardware

## •Probe temperature telemetry during cruise

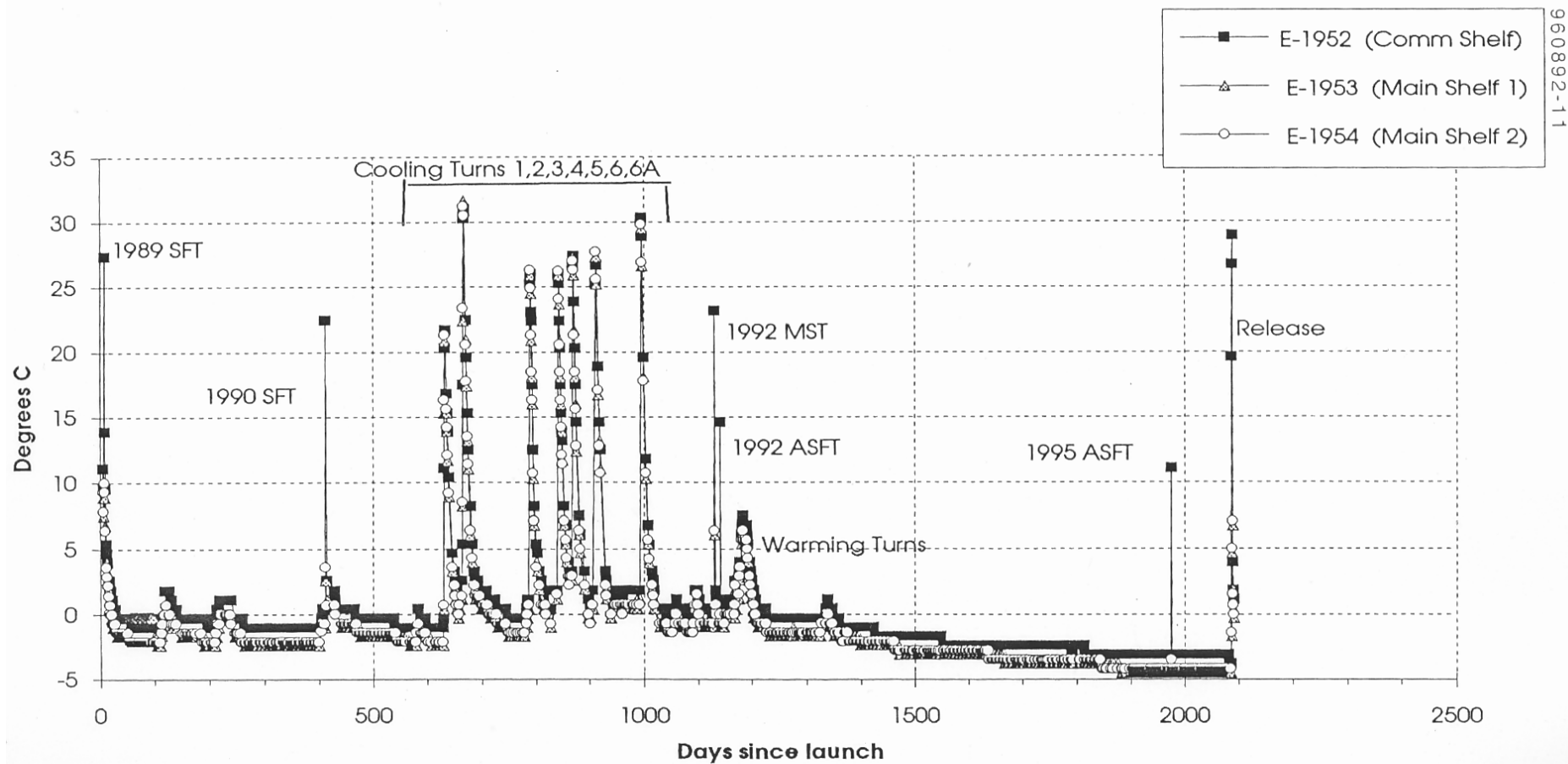
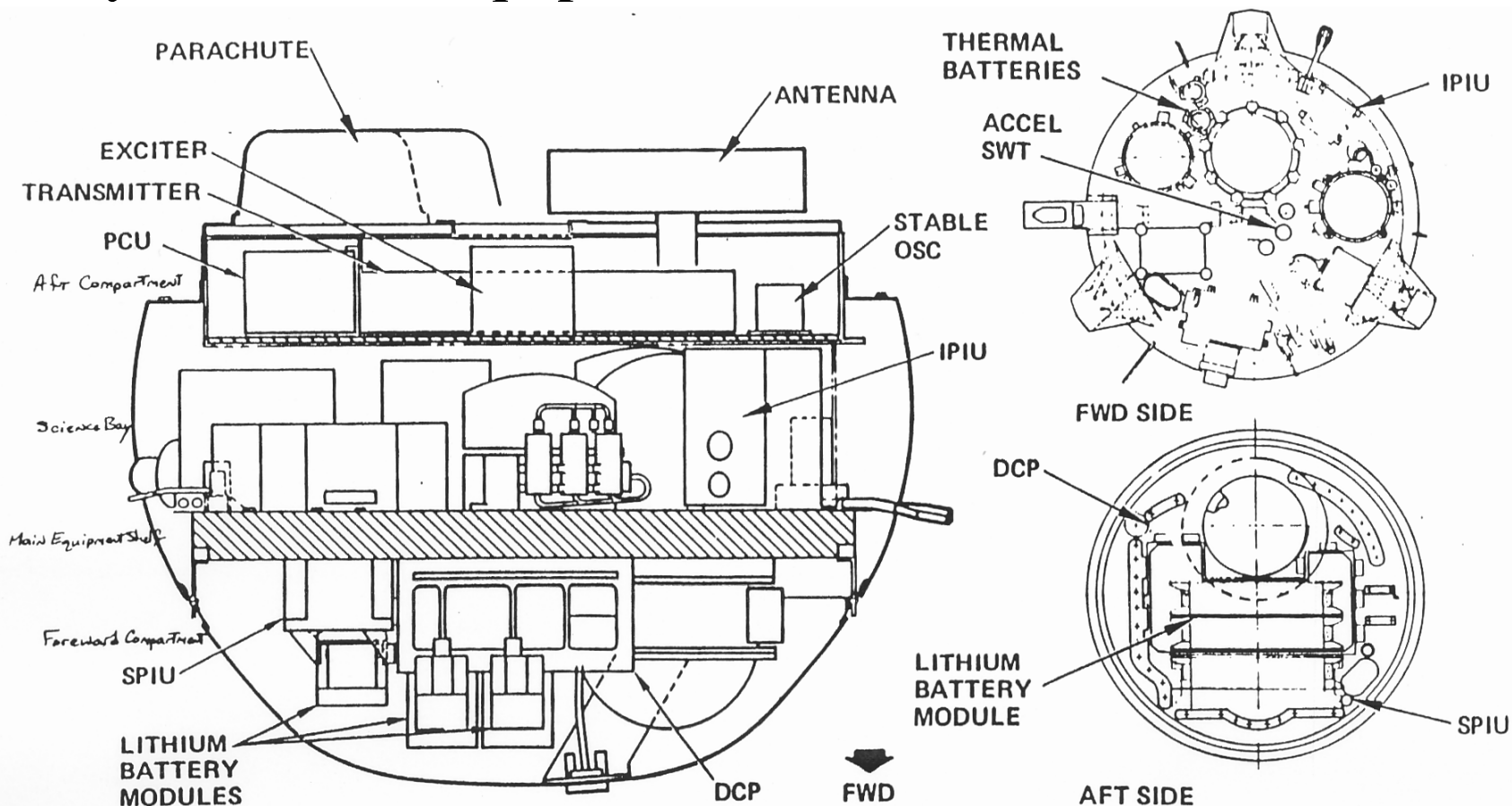


Figure 2.8-1. Cruise Shelf Temperatures

- **Probe Descent - two noted conditions**
  - First parachute deployment occurred 53 seconds later than planned
    - equivalent to 5 minutes of parachute descent (of about 60 minutes total)
    - cause blamed on crossed harness wires between G-switches & DCP
    - Probe mission started deeper in atmosphere than expected
      - higher dynamic load due to denser atmosphere when chute deploys
      - all dynamic loads determined to be less than qualification levels
    - no significant impact to data return or mission science
    - no significant impact to Probe temperatures or thermal control
      - theory higher dynamic loads cause MLI to separate resulting in poor performance
      - tested well beyond 228 g entry force, not believed to cause of thermal extremes
  - Second noted condition was that Probe temperature extremes were cooler initially & then hotter during later stages of Descent
    - pre-entry temperature matched thermal predict (end of Coast phase)
      - verified by telemetry both at 3 hours & at 20 minutes prior to entry
      - thermal control (gold tape) survived maneuvers & performed as expected
    - atmospheric composition very close to predicts, not the cause
    - indicates greater heat transfer to environment than expected during descent

## •Layout of Probe equipment



## •Flight Atmosphere & Aerofairing Temperatures

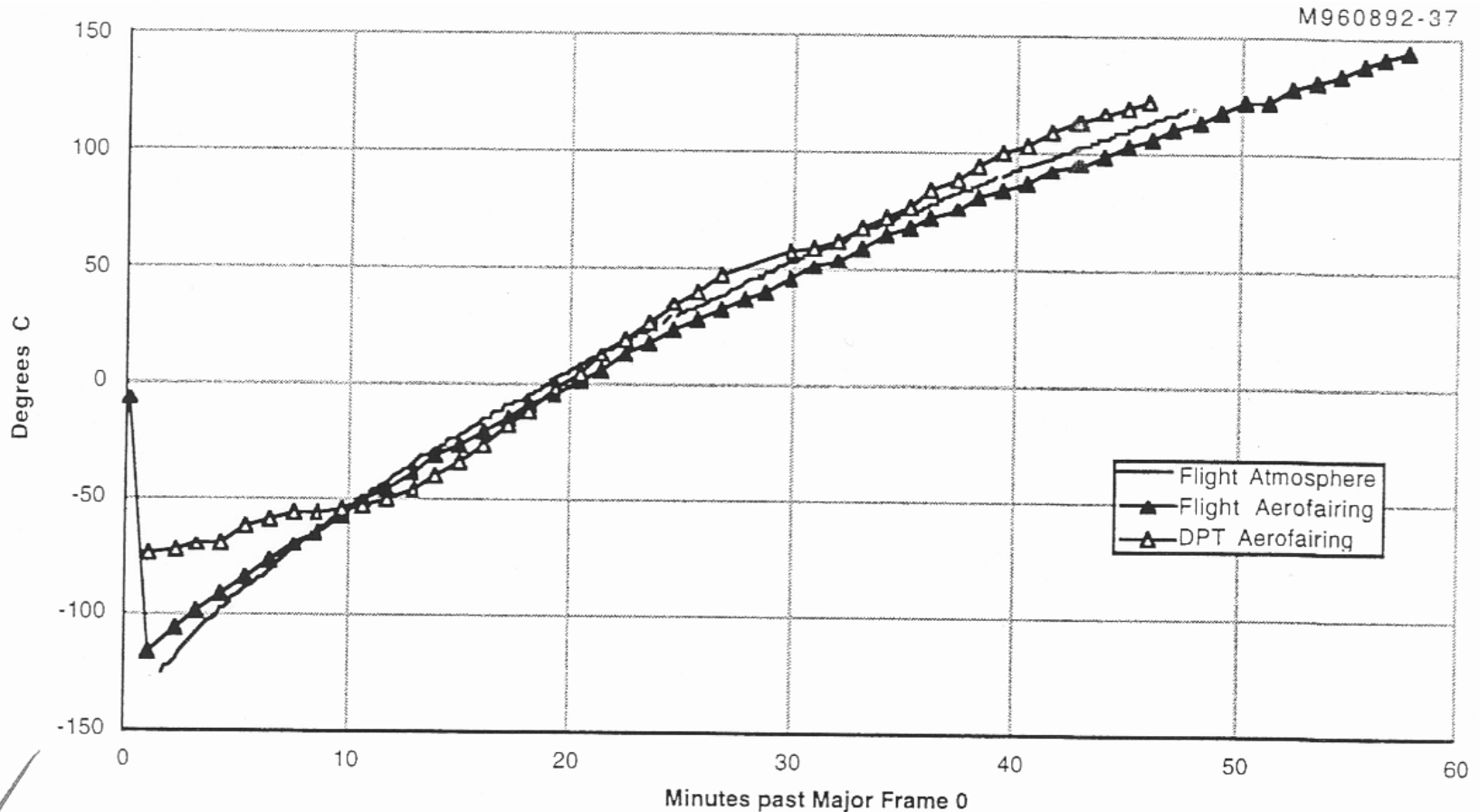


Figure 3.6-1. Flight and DPT Aerofairing Temperatures (Along With ASI Atmospheric Temperature Data)

- **Probe Descent met all requirements, successful mission**
  - Contract requirement for one string function down to 10 bar pressure or to reach 0.1 bar plus 48 minutes (turned out to be 13 bars)
    - Probe clearly met both contractual requirements, 100% successful mission
    - all science instruments collected valid data to 10 bars, Entry (E)+35 minutes
      - most science instruments gathered data well beyond that
    - all instruments maintained within Acceptance range down to E+48 minutes
  - Pre-launch time requirement interpreted to be E+51.3 minutes
    - noted pre-launch goal to be E+60 minutes, not a requirement
    - post-launch goal was changed to E+75 minutes, not a requirement
  - Transmitter (TX) reached its 60°C qualification limit at E+38 minutes
    - kept functioning up to 115°C when both strings shut down at E+59 minutes
  - All hardware continued to function well beyond its Qual temperature
    - should have gathered calibration data beyond Qual range
    - used EM units at JPL to gather calibration data after descent
  - Final contract close-out conclusion - “**All Probe subsystems met or exceeded the mission duration requirements**”

## • Descent temperature data

- Science bay & aft compartment (communication bay) temperatures noticeably more extreme than predicted
  - slightly colder during initial entry & hotter at end of mission
  - Helium Abundance Detector (HAD) right on predicts
    - Be chassis, foam & MLI enclosure, isolated inlet-unit & unit-shelf
  - Neutral Mass Spectrometer (NMS) also matched predicts
    - large unit individually isolated from Probe environment
- Forward bay temperatures much closer to predicts
  - main batteries & DCP unit, large massive units
- Sample of extreme temperatures
  - cold generally at E+1.1 minutes, hot always at E+59 minutes
    - Aerofairing                      -116°C to +145°C
    - Transmitter                      -18°C to +115°C
    - Main shelf                      -30°C to +106°C
    - DCP                      -11°C to +57°C
    - Main batteries                      -4°C to +49°C

- **Descent Pressure/Temperature Test (DPT)**
  - DPT ground test data used in place of analytical models
    - Pre-launch analytical model not simulating developmental test results
    - analytical models abandoned, used DPT empirical data only
  - Final DPT comprised of flight hardware except science instruments Engineering Models & no live pyro/separation devices
    - goal to simulate thermal conditions down to E+48 minutes
    - chamber unable to quench, required to cool  $> 100^{\circ}\text{C}$  in 64 seconds
      - initial cool down based on extracting equivalent amount of energy
  - Significant differences between DPT & flight not accounted for until post-entry correlation
    - DPT performed in 1-g vs. 2.6g in flight, not feasible to simulate higher g
      - natural convection proportional to  $g^{0.3}$  & buoyancy proportional to  $g^{0.5}$
    - DPT 100% He vs. 10% He + 90%  $\text{H}_2$  in flight, safety issue in test
      - different properties of  $\text{H}_2$  enhances buoyancy & convection, viscosity 2x higher
    - DPT stagnant vs. full aerodynamically driven motion in flight
      - dynamic motion in flight greatly enhances convection & mass movement
      - flight spinning at 10 RPM plus 250 disturbances of  $\pm 0.6\text{m/s}^2$  every 96 seconds

## •Transmitter Temperatures, Flight & DPT

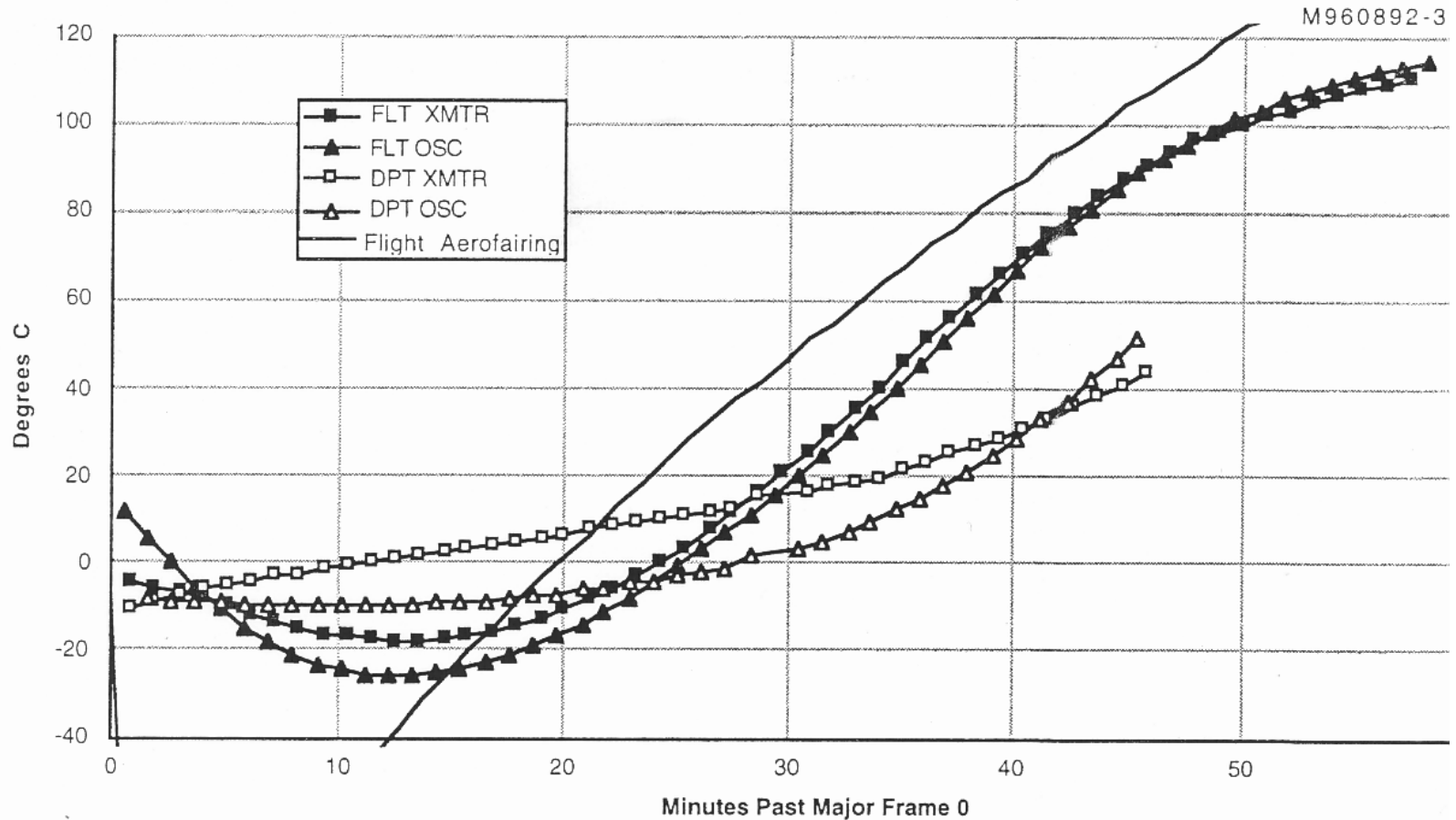


Figure 3.6-3. USO and Transmit Temperatures for Communication Shelf

## • DCP Temperatures, Flight & DPT

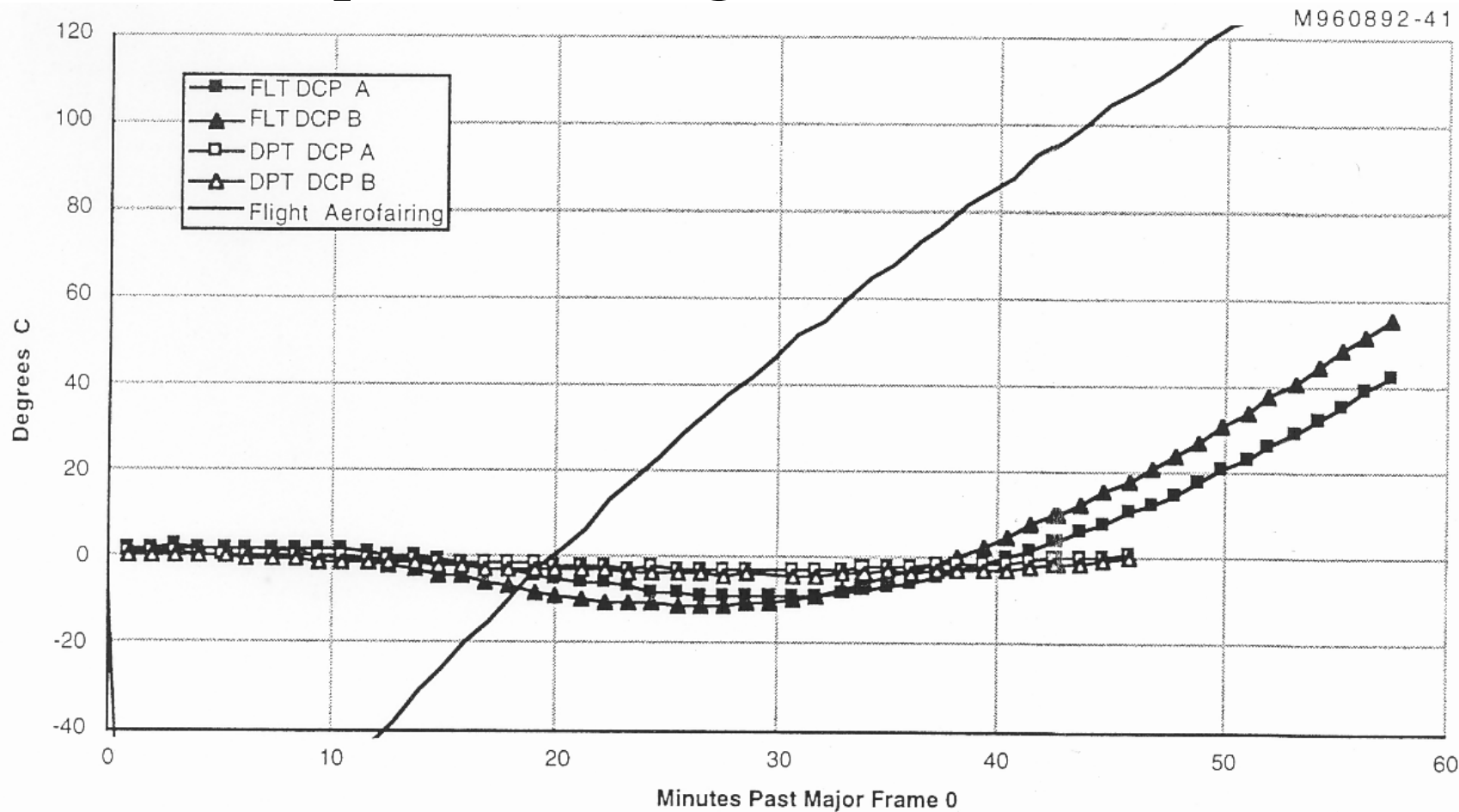


Figure 3.6-5. DCP Temperatures

# • Main Battery Temperatures, Flight & DPT

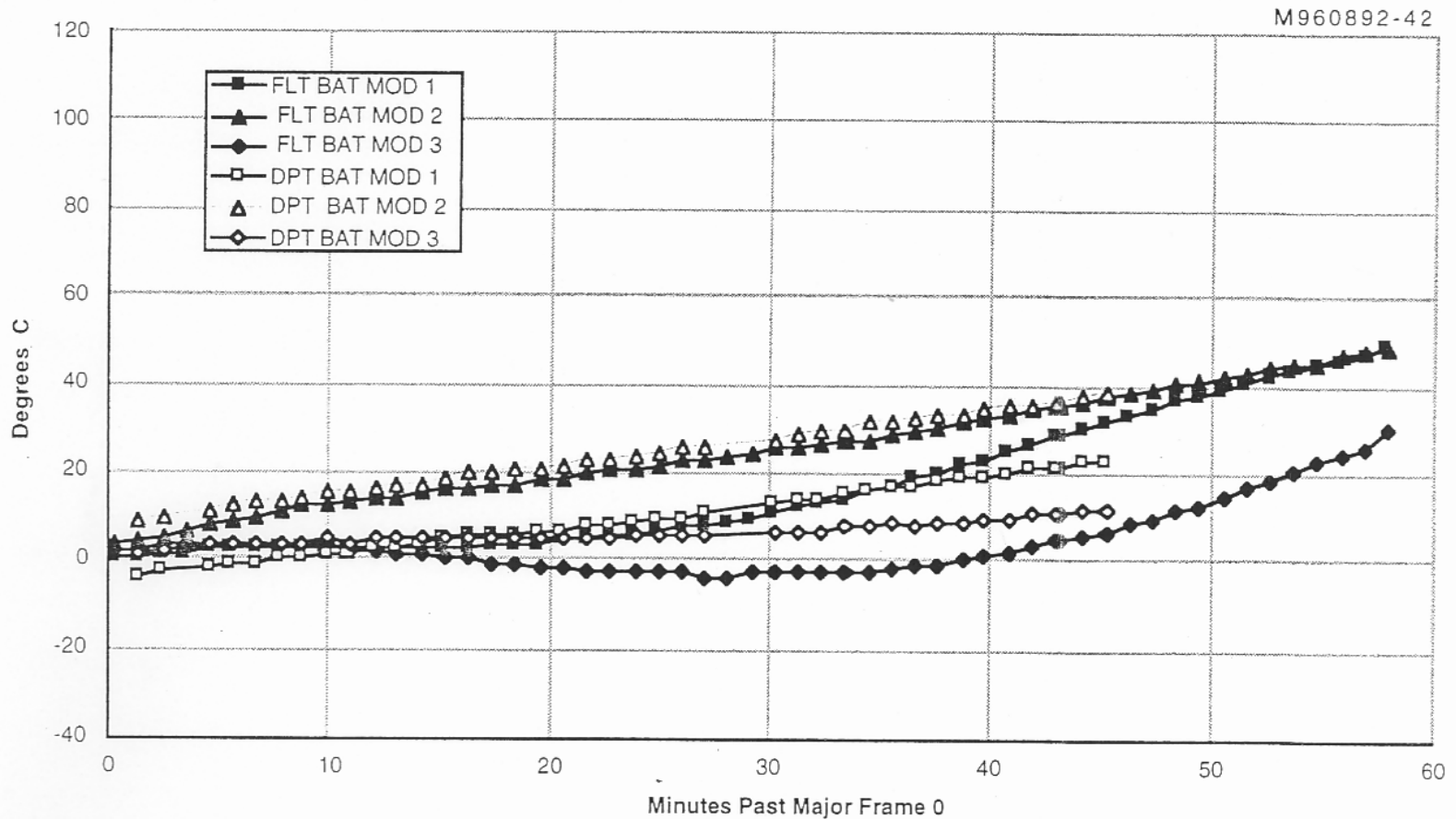


Figure 3.6-6. Battery Modules

## • Correlation of Flight to DPT data

- Created new Probe thermal model with advanced modeling techniques
  - significant improvements in analysis techniques between 1983 & 1997
  - 1997 model tools included MSC/Patran, TRASYS, & HSCinda
    - more advanced tools available today (Sinda/Fluint for thermal-fluid coupling)
- Model constructed to easily changed 4 critical thermal parameters
  - convection heat transfer coefficient
  - mass entry & flow rate
  - Probe spin rate
  - gas buoyancy contribution
- Initially calculated flight parameters close to matching flight data
  - increased buoyancy term 10x to better match flight data, no other changes
- Applied parameters to DPT after correcting for known differences
  - decreased convection term by 0.76 & buoyancy term by 0.58 to account for gravity & gas property differences
  - initially not well matched to DPT data, temperatures too extreme
    - needed to also drop convection coefficient by 10x to better match DPT data
    - large mass flow decrease would not match data, concluded no flight MLI failure
  - Why such a large increase in convection between DPT & flight?
    - flight spinning at 10 RPM plus 250 disturbances of  $\pm 0.6\text{m/s}^2$  every 96 seconds
    - increased buffeting, turbulence, & small increased flow accounts for differences

## • Lessons learned & recommendations for future

- Improve analytical modeling capability, don't just ignore analysis
  - **pre-launch temperatures based strictly on DPT data, no test is ever 100% flight-like**
    - always need combination of both test & analysis
  - **Probe Descent analyses must include coupled thermal & aerodynamic effects**
    - even if sealed, buffeting & movement significantly impacts convection internal to Probe
- Diligence required in identifying differences between test & flight
  - **BSDC has better system in place today with extensive 'test as you fly' reviews**
  - **no emphasis in 1983 to identify & account for differences in DPT vs. flight**
  - **post-entry correlation revealed several differences that were not taken into account**
- Obtain calibration data well beyond the expected temperature extremes
  - **equipment will most likely survive & produce data beyond its Qualification range**
    - knew data would be gathered until it stopped coming, calibrate over widest range possible
  - **system margin did not account for any extremes beyond expected temperatures**
    - during DPT units saw -14°C, only 6°C margin on cold end to calibration limit of -20°C
    - similarly not much margin on hot end, DPT data at +44°C vs. +60°C calibration limit
- Consider individual insulation systems and/or sealed entry vessel
  - **BSDC Pioneer Venus Probe temperatures matched entry predicts with sealed vessel**
    - beware of other complications, sealed vessels have their own peculiar set of problems
  - **use foam plus individual unit blankets along with larger cavity close-out blankets (redundant insulation systems) to limit convective currents & mass flow**
    - Helium Abundance Detector (HAD) implemented this & was most benign thermally of all science instruments

## • References

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4. 1997 AIAA Applied Aerodynamics, Plasmadynamics and Lasers, and Thermophysics Conference 97-2456, "Galileo Probe Descent Post-Flight Thermal Correlation Analysis," Brian Mischel, Tom Rust, and Fred Linkchorst, 23 June 1997.